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CONVECTIVE CLOUD CELLS AS OBSERVED FROM ARTIFICIAL EARTH SATELLITES

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ABSTRACT. A series of photographs showing convective cloud cells, taken by the "Cosmos-122" satellite, are analyzed. Data from a statistical analysis of the results of measurements of the horizontal dimensions of cloud cells with descending movements at the center are presented. Graphs are plotted showing the horizontal dimensions of the cloud cells as functions of the thickness of the convective layer and the vertical temperature gradient.

There is a discussion of the effect of moisture on the structure of convective cells, and characteristic values are given for the wind speed at ground level in synoptic situations favorable to the development of symmetric convective cells. Empirical data on the structure of convective cells are compared with the results of theoretical studies involving ordered convection. It is concluded that television pictures of symmetric convective cells can be used to estimate the thickness of the convective layer, the vertical temperature gradient and the humidity of the air in this layer. 5 illustrations, 11 bibliographic entries.

The television apparatus installed in modern satellites has a resolving /22* power on the order of several kilometers, making it possible to detect morphological features of cloud fields of medium and synoptic scale. In particular, television pictures often reveal symmetric convective cells whose horizontal dimensions vary from several kilometers to several tens of kilometers. It has not been possible to observe this interesting phenomenon with the aid of ordinary network observations, since the observer's field of vision is insufficient to detect structural features of such scale.

After symmetric convective cells were found in television pictures of

* Numbers in the margin indicate the pagination in the original foreign text.

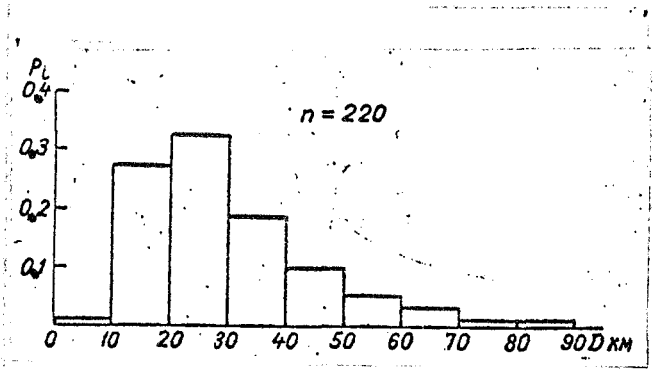

Figure 1. Empirical Distribution of Diameters of Convective Cells with Descending Movements at the Center.

Here and in Figures 2 - 4, n = the Number of Models.

cloud cover, articles appeared in the scientific literature containing aerological analyses of individual situations involving convective cloud cells [1, 4, 9]. In contrast to previous papers, the present article deals with a comparatively large series of observations. We used television pictures of cloud cover taken by the "Cosmos-122" satellite and conventional aerological data as the raw material.

In the course of our study of the television pictures, we noted that "open" convective cells were found in the atmosphere somewhat more frequently than "closed" ones(1). Since the number of models with "closed" cells turned out to be small, we have restricted ourselves in the following to only those convective cells with descending movements at the center.

We began by determining the characteristic horizontal dimensions of cloud cells. In the histogram in Figure 1, it is apparent that the diameter of convective cells is most often equal to 20 - 30 km, and in 80% of the cases it is between 10 and 40 km. We also determined the relationship between the cloudy and cloudless spaces within a convective cell. As a result of the analysis of data from 220 measurements, we were able to conclude that the radius of the cloudless space is usually somewhat less than the radius of the cloud ring (in 52% of the cases, $r_{\text{cloudless}}/r_{\text{cloudy}} < 1$). There were /23

(1) In the following, we shall use the concept of "open" convective cells to describe cells of a circular or hexagonal shape with descending movements at the center. "Closed" cells will be those in the shape of a polygon (usually a hexagon) with ascending movements at the center and descending movements at the periphery.

relatively few cases in which the radius of the cloudless space was considerably larger than the radius of the cloud ring ($r_{cloudless}/r_{cloudy} > 2 \approx 17\%$).

The problem of the interaction of the scale of the horizontal movements with the thickness of the convective layer and the vertical temperature gradient in this layer is a very interesting question from both the theoretical and practical standpoints. The thickness of the convective layer was determined from data from temperature soundings in regions occupied by convective cells. In view of the fact that true convective cells develop exclusively above equatorial oceans, where the network from making atmospheric soundings is extremely sparse, a total of 22 cases of cell-type convection were analyzed. It was found that the thickness of the convective layer in the presence of /24 convective cloud cells was usually 2 to 2.5 km, while in 95% of the cases the thickness of the convective layer did not exceed 3 km. This indicates that true polygonal convection develops in a comparatively shallow layer of the atmosphere. As a matter of fact, in regions with convective cells, the ground stations recorded cumuliform and strato-cumulus clouds in 82% of the cases and cumulo-nimbus clouds in only 18% of the cases.

The horizontal dimension (diameter) of the convective cells is plotted as a function of the thickness of the convective layer in Figure 2. It is easy to see from the distribution of the points in this figure that there is no close relationship between the size of the cell and the thickness of the convective layer. The ratio of the diameter of the convective cell (D) to the thickness of the convective layer (h) is equal to 34 on the average, and in 80% of the cases $10 \leq D/h \leq 50$.

The relationship between the vertical temperature gradient and the horizontal dimensions of the convective cells is a matter of definite theoretical and practical interest. As a result of statistical analysis of rawinsonde data it was found that the vertical temperature gradient in the presence of symmetric convective cells is equal to 0.82 degrees/100 m on the average,

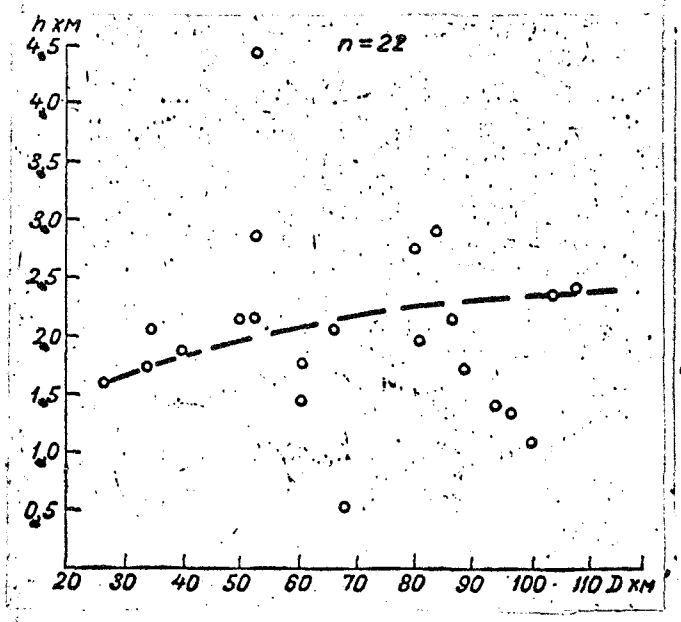

Figure 2. Cell Diameter versus Convective Layer Thickness.

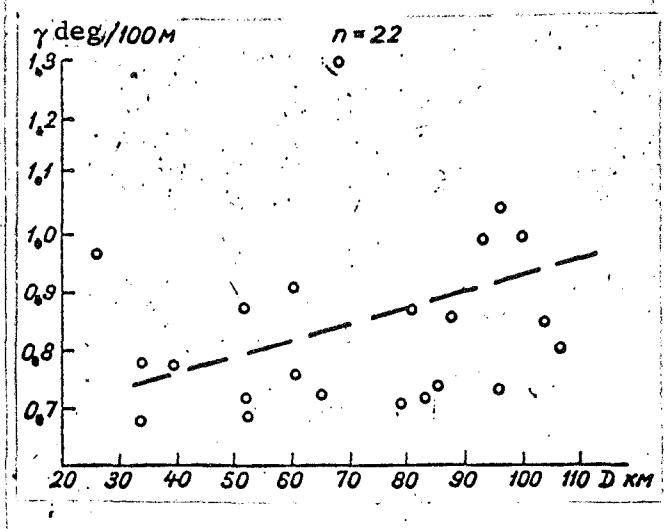

Figure 3. Cell Diameter versus Mean Temperature Gradient in the Convective Layer.

and it exceeds the moist-adiabatic gradient in almost all the cases considered. The dependence of the horizontal dimension of convective cells on the temperature gradient in the convective layer is shown in Figure 3. It is clear from the distribution of points in this figure that the size of the convective cells increases with an increase in the vertical temperature gradient, but the scatter of the points is rather large. It should also be mentioned that an increase in temperature gradient is accompanied by a decrease in the ratio $r_{cloudless}/r_{cloudy}$. Thus, at γ = 0.65 degrees/100 m it is 1.4, at γ = 0.8 degrees/100 m it is 0.7, and at γ = 1.0 degrees/100 m it is 0.3. Hence, the value of $r_{cloudless}/r_{cloudy}$ can serve as an indicator of the vertical temperature gradient in the convective layer.

The statistical analysis which we performed would not be complete if we had not considered the effect of humidity on the structure of convective cells. It is natural to assume that as the humidity increases, the ratio of the cloudless area to the cloudy area within the limits of the cell must /25

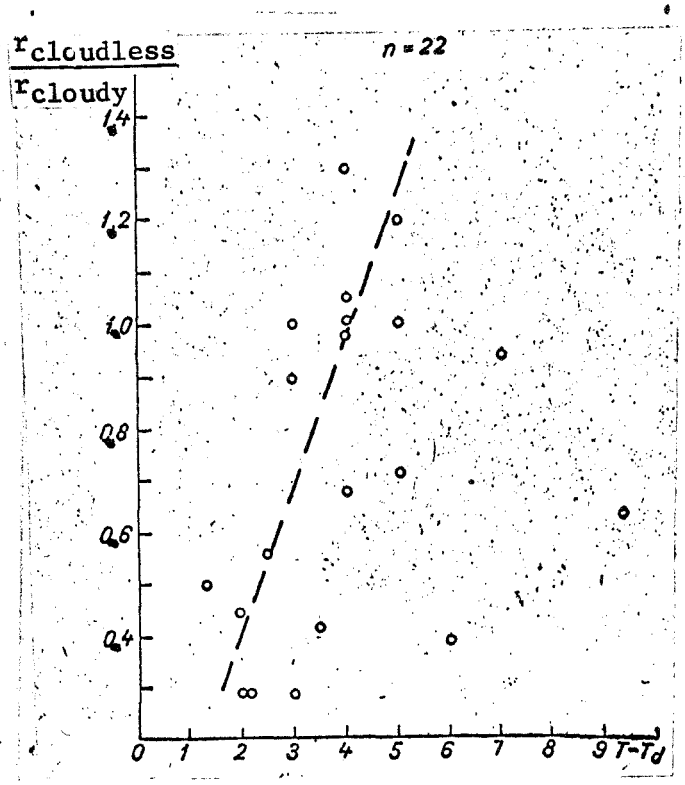

Figure 4. Relationship Between Dew Point Deficit and Ratio of Cloudy and Cloudless Spaces in the Convective Cell.

decrease. Empirical data characterizing this relationship are shown in Figure 4. It is clear from the distribution of points in this figure that at $r_{cloudless}/r_{cloudy} = 0.4$ the dew point deficit is 2°, while at $r_{cloudless}/r_{cloudy} = 1.3$ it is 5°.

Symmetric convective cells, which develop under the influence of buoyancy, can retain their shape only in the event that no air current has a deforming effect on them. We can therefore expect that in those cases when there is convective symmetric cloud cover in the atmosphere, the speed of the air flow (and most important, the vertical wind shear) must be insignificant. Statistical analysis of rawinsonde data has shown that when there are symmetric convective cells the wind speed at ground level is equal to 7 m/sec on the average and does not exceed 10 m/sec in 80% of the cases. The vertical wind shear and the curvature of the wind profile (d^2V/dz^2) are insignificant. As the wind speed increases, the symmetric convective cells are subsequently transformed into sickle-shaped cloud formations (the clouds are eroded on the windward side) and then into banks. Such a transformation process is clearly evident in the television pictures of cloud cover over the North Atlantic taken by "Cosmos-122" on 10 October, 1965 (Figure 5). This photograph clearly shows the cloud cover in the form of /26
symmetric convective cells at the periphery of a cyclone in region A. As we come closer to the center of the cyclone, the rate of air flow increases, and the symmetric convective cells are gradually transformed into cloud banks.

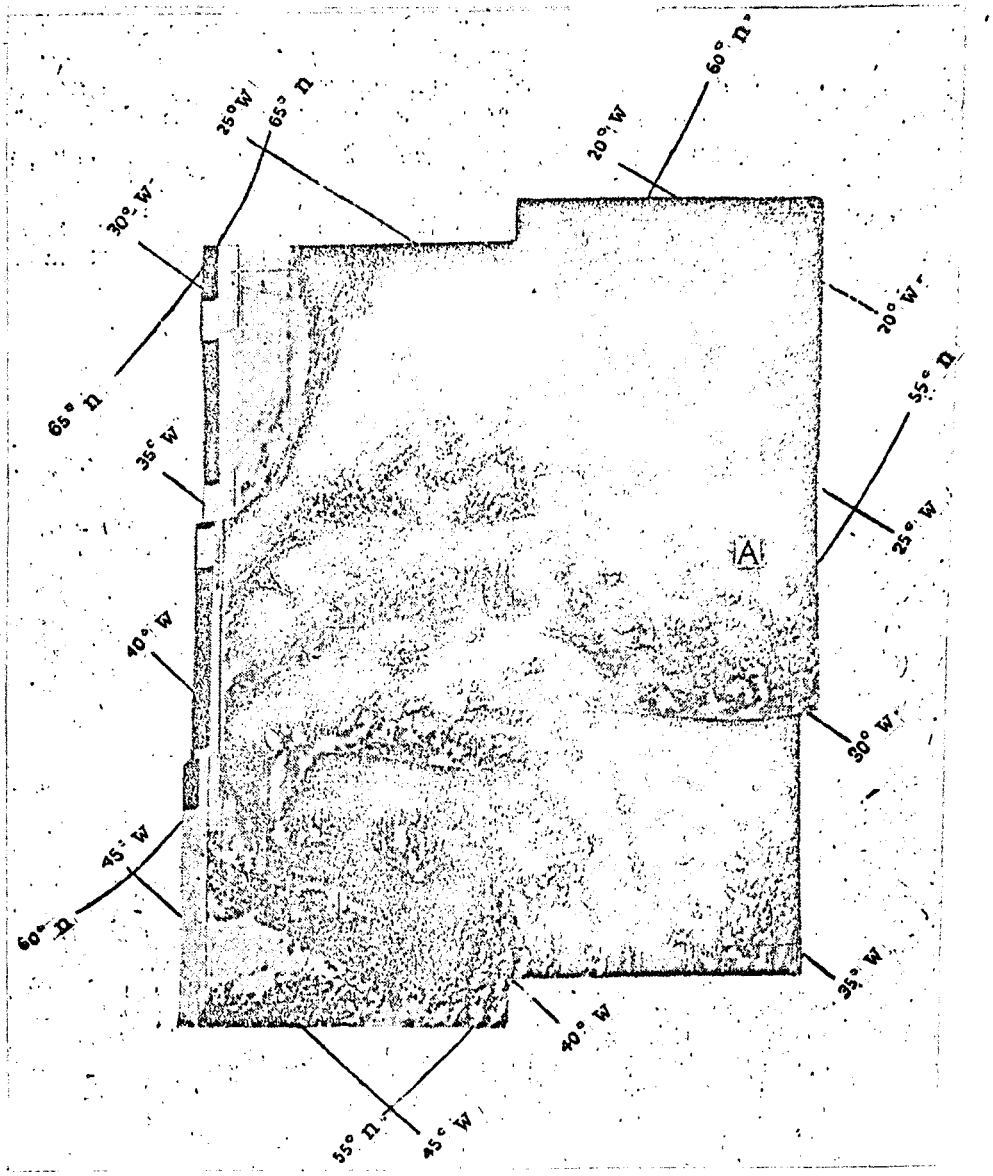

Figure 5. Television Picture of Cloud Cover Taken by "Cosmos-122" Satellite on 10 October, 1966 at 1620 Hours Moscow Time.

ANALYSIS OF THE RESULTS

The study of the television pictures showed that symmetric cells with descending movements at the center occur somewhat more often in the atmosphere than do those with ascending movements. As early as 1933, Graham [3] suggested, on the basis of experimental data, that hexagonal cells with ascending movements at the center form in fluids in which viscosity decreases with in- /27

creasing temperature, while cells with descending movements form in gases in which viscosity increases with temperature. Palm [7] and Segel and Stuart [10] confirmed the accuracy of this view on the basis of a nonlinear analysis with consideration of the changes in viscosity as a function of temperature. The data we obtained support the results of these authors. In fact, true cells with descending movements at the center are apparently preferred in the atmosphere (as in a gaseous medium). Nevertheless, there are true hexagonal cells with ascending movements at the center. Hence, one kind of wind circulation or another within a cell is caused not only by the physical properties of the medium but also by a certain distribution of parameters characterizing the state of the atmosphere.

It is mentioned in [1] that convective cells with descending movements in the center are formed during rapid heating of air masses and cylonic curvature of the air flow, while convective cells with ascending movements in the center are formed during slower heating of air masses and anticyclonic curvature of the air flow. The analysis of 30 cases which we performed indicates that during the formation of convective cells with descending movements at the center, cyclonic curvature of the air flow occurs at ground level in 75% of the cases and at the 500 mb level in 80% of the cases. Hence, the results presented in [1] are supported, but the physical conditions that allow realization of one or the other form of circulation within the cell remain incompletely clear.

The second problem, touched on only partially in the present article, is the dependence of cell geometry on vertical temperature distribution and other parameters characterizing the state of the atmosphere. The linear theory of stability does not answer this question [2], since it only allows conclusions to be drawn regarding the value of the wave vector. It is known, however, that the wave vector can be decomposed into two orthogonal components by an infinite number of methods, and so the structure of the convective cell remains completely indeterminate. On the basis of an analysis

of the finite amplitudes, Segel [11] showed that cell convection begins in a slightly subcritical situation (compared to linear theory), in which the interaction of a finite number of disturbances having the same general wave number forms a stable hexagonal cell. If the Rayleigh number increases further, the hexagonal state of equilibrium becomes unstable (beginning at some critical value) and is replaced by a stable state in the form of two-dimensional swells. Analysis of television pictures of cloud covers supports this conclusion qualitatively. As a matter of fact, symmetric hexagonal cells do not develop over land, even if it is rather level. This is evidently related to the fact that the land heats up much more rapidly during the day than the surface of the ocean. The Rayleigh number, which depends on the vertical temperature gradient, increases rapidly, and the possible states of equilibrium are two-dimensional swells or cells of rectangular shape, which lead to the appearance of cloud banks. Hence, with all other conditions equal, symmetric cells tell more about the stability of the atmosphere than do cloud banks.

The next important problem is the interaction between the horizontal scale of the convective cell and the thickness of the convective layer. The /28
linear theory of stability gives the following relationship for the case of free boundaries:

$$D = 2\sqrt[3]{2}\,h \tag{1}$$

where h is the thickness of the convective layer, and D is the wavelength. According to the data acquired in the present study, D/h is equal to 34 on the average, i.e., it is an order of magnitude greater than the value which follows from linear theory. It should be mentioned that the laboratory experiments show an agreement with theory that is not bad, since this type of divergence must be sought in the characteristic features of the atmosphere. The data presented in this article agree with the results of individual measurements contained in the work of Kreuger and Fritz [4]. It should be noted that the coefficient of kinematic viscosity is assumed to be isotropic in

the majority of theoretical papers devoted to convection. These conditions are also rather well fulfilled in the laboratory experiments. In considering the convective processes in the atmosphere, when the horizontal dimensions of the convective cells are on the order of tens of kilometers, the assumption of isotropicity in the vertical and horizontal directions may not be fulfilled. Ray [8] considered the effect of non-isotropicity of turbulent viscosity and conductivity on the ratio of the horizontal dimension of the cell to the vertical thickness of the convective layer. On the basis of linear theory, he came to the conclusion that in this case, when the coefficients of turbulent viscosity and conductivity in the horizontal direction are two orders of magnitude greater than the value in the vertical direction, the ratio D/h is on the order of the values observed in the atmosphere. In particular, at $K_h = 500\ K_v$ and $\nu_h = 100\ \nu_v$, D/h = 30, which is in complete agreement with the results in this paper.

The formula given above establishes a direct link between the horizontal dimension of the convective cell and the vertical thickness of the convective layer, the coefficient of proportionality being $2^{2/3} > 1$. The results listed in Figure 1 indicate that under real atmospheric conditions an increase in the horizontal dimensions of the convective cells results in only an insignificant increase in the thickness of the convective layer. Hence, the conclusions regarding the interaction of the vertical and horizontal scales that follows from the linear theory of stability unfortunately cannot be applied to atmospheric conditions.

In a more detailed consideration of atmospheric convection, we must take into account the effects produced by condensation and evaporation. The convective movements in a conditionally unstable atmosphere were discussed in considerable detail in the works of Kuo Siao-Lan' [5, 6]. He obtained an approximate ratio that links the dimensions of the cloudy and cloudless parts of the cell as a function of the atmospheric stratification:

$$\frac{r_{cloudy}}{r_{cloudless}} = \frac{\gamma - \gamma_{ma}}{\gamma_a - \gamma'} \qquad (2)$$

where γ_v is the moist-adiabatic and γ_a the adiabatic temperature gradient. It follows from this expression that as the true temperature gradient increases and the moist-adiabatic gradient decreases, the relative dimensions of the cloudy sections must increase. The results of calculations using this formula were compared by us with actual data (the number of medels was 20). It was found that there is a general tendence toward an increase in the ratio /29 $r_{cloudy}/r_{cloudless}$ with an increase in the parameter $\frac{\gamma - \gamma_{ma}}{\gamma_a - \gamma}$, but the true values of $r_{cloudy}/r_{cloudless}$ are approximately 1.5 - 2 times greater than the calculated values. This may be due partially (as the author himself pointed out) to the fact that the clouds usually shift into regions of descending movements.

The statistical data presented in this paper regarding the conditions for formation of cellular convective clouds are based on a comparatively small number of models, so that the conclusions which are drawn below must be considered preliminary.

Convective cells of symmetric shape arise in regions with relatively small wind speeds ($V_{av} \approx 7$ m/sec).

The vertical temperature gradient in convective cells exceeds the moist-adiabatic and is equal to 0.8 degrees/100 m on the average. The thickness of the convective layer as a rule does not exceed 3 km, while the average ratio of the cell diameter to the thickness of the convective layer is 34.

As the thickness of the convective layer increases, there is a slight increase in the cell diameter (see Figure 2). As the temperature gradient increases, the horizontal dimension of the cell also increases (see Figure

3); the increase in the ratio $r_{cloudy}/r_{cloudless}$ is accompanied by an increase in the temperature gradient and humidity of the air (see Figure 4).

Hence, data on symmetric convective cells can be used to estimate the thickness of the convective layer, the vertical temperature gradient and the humidity of the air in this layer. In addition, a symmetric state of the convective cells suggests low speeds for the air flow in regions where they form, which is important for estimating the state of the atmosphere above equatorial oceans where the network of meteorological stations is extremely sparse.

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